S 100 26 and 27

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Science Foundation Course Units 26 and 27

Earth History I and II

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Science Foundation Course Unit 27

EARTH HISTORY: 2

Prepared by the Science Foundation Course Team

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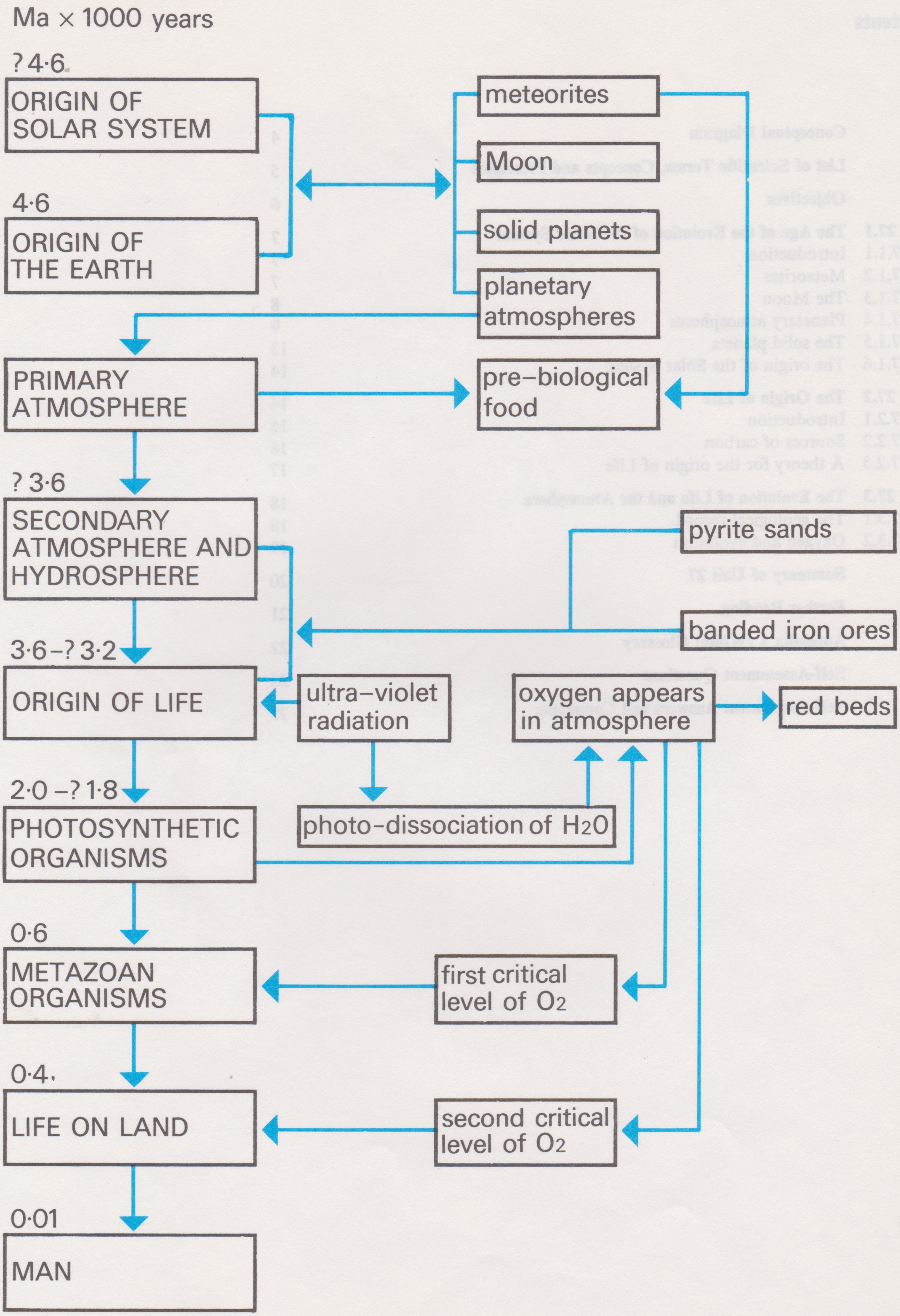

Ma × 1000 years
?4·6
ORIGIN OF SOLAR SYSTEM
4·6
ORIGIN OF THE EARTH
meteorites
Moon
solid planets
planetary atmospheres
PRIMARY ATMOSPHERE
pre–biological food
?3·6
SECONDARY ATMOSPHERE AND HYDROSPHERE
pyrite sands
banded iron ores
3·6–?3·2
ORIGIN OF LIFE
ultra–violet radiation
oxygen appears in atmosphere
red beds
2·0 –?1·8
PHOTOSYNTHETIC ORGANISMS
photo–dissociation of H2O
0·6
METAZOAN ORGANISMS
first critical level of O2
0·4
LIFE ON LAND
second critical level of O2
0·01
MAN

Table A

List of Scientific Terms, Concepts and Principles used in Unit 27

Taken as pre-requisites			**Introduced in this Unit**			
1	2		3		4	
Assumed from general knowledge	**Introduced in a previous Unit**	**Unit No.**	**Defined and developed in this Unit**	**Page No.**	**Introduced here, but fully developed in a later Unit**	**Unit No.**
meteorites	petrology	24	*In Unit*			
metallurgy	asteroids	22	irons	8		
ozone	inner planets	22	maria	8		
	outer planets	22	lunar highlands	8		
	magnetosphere	23	craters	9		
	emission spectra	6	outgassing vs impact origin of lunar craters	9		
	absorption spectra	6	Doppler effect	10		
	gravitational constant	3	escape velocity	11		
	Maxwellian distribution of molecular velocities	5	observed composition of planetary atmospheres	11		
	Earth's liquid Fe-core	22	predicted atmospheres	12		
	Miller experiment	21	protoplanets	14		
	weathering	24	primary atmosphere	16		
	respiration	15	prebiological food	16		
	fermentation	18	secondary atmosphere	16		
	mitochondria	14				
	photosynthesis	15	*In Understanding the Earth*			
			nebular hypothesis	62–4		
			'tidal' hypothesis	62–4		
			achondrites	116–17		
			carbonaceous chondrites	116–17		
			chondrites	116–17		
			stony irons	116–17		
			Urey level	145		
			First critical level	146		
			Second critical level	148		

Any scientific terms used in this Unit but not listed are marked thus † and defined in the glossary (p. 22).

Objectives

When you have completed this Unit, you should be able to:

1 Define, or recognize adequate definitions of, or distinguish between true and false statements concerning each of the terms, concepts and principles given in column 3 of Table A.

2 Outline the major differences between the inner and outer planets.

3 Select lines of evidence which suggest the great antiquity of the lunar surface features in contrast to those of the Earth's surface.

4 Given the necessary data for a planet, calculate its escape velocity, and hence suggest the likely composition of its primary atmosphere.

5 Outline two possible sources of prebiological food, and describe their synthesis.

6 Given data concerning mineral stability, and the distribution of such minerals through geological time, make deductions concerning the composition of the atmosphere for a particular period.

7 Correctly recognize processes contributing to the formation of the Earth's atmosphere.

Section 1

27.1 The Age of the Evolution of the Solar System

27.1.1 Introduction

So far in this course we have been describing the major features of the Earth, both at the present time and during the past 600 Ma. In Unit 22 we described the main features of the internal structure of the Earth, and in Unit 23 the Earth's magnetic field was discussed, leading to the idea that the Earth has a liquid nickel-iron core. In Units 24 and 25, the major Earth's surface features were described, and processes were suggested to account for their formation. In Unit 26 we began to examine the Earth's history and to show how a detailed picture of it is built up using the maxim that the 'present is the key to the past'.

The concept of uniformitarianism was applied across a wide spectrum, from sand grains to crustal movement, suggesting that similar conditions and processes have persisted over long periods of geological time. But how successfully can we apply this concept when trying to answer questions concerning the age and formation of the planetary system, and the evolution of atmosphere and life on Earth?

The investigation of such remote periods is difficult, for even the oldest rocks on the Earth (those 3 600 Ma old) do not appear to record the earliest events in Earth history. The only other parts of the Solar System available to us for laboratory studies are meteorites, and the recently obtained lunar samples. But it is, of course, possible to make inferences, based on our observations, about the planets in the Solar System and, by applying uniformitarian principles, to deduce what their ancient histories might have been. We shall review some of the data available for other members of the Solar System before examining the Earth's history.

27.1.2 Meteorites

Read Chapter 8 in *Understanding the Earth*, which summarizes our present knowledge of meteoritic material. Whilst reading this Chapter do not worry too much about unfamiliar terminology, except for items listed in Table A, which we suggest you look at again before reading the Chapter. After you have read it, you should be able to describe the main classes of meteorite, say something about the differences in chemical composition between them and the Earth's crust, and make inferences concerning the planetary body or bodies from which they came. You should also recognize that meteorites are at least 1 000 Ma older than the oldest rocks so far dated on Earth. Data concerning the temperature and possible cooling rates of meteoritic material have been calculated from experimental work in the fields of metallurgy (for the iron meteorites) and experimental petrology (for the silicate components of meteorites).

When you have read Chapter 8 attempt SAQs *1–4*.

Summary

Measurement on photographs taken at several points on the Earth's surface enables the trajectories of meteorites entering the Earth's atmosphere to be calculated. These show that meteorites have elliptical orbits, the outermost parts of which reach the asteroid belt between Mars and Jupiter. It is therefore assumed that the meteoritic material reaching the Earth is derived from the asteroids. Meteorites (and lunar samples) have provided the oldest rock materials known, up to 4 600 Ma in age. (This figure agrees with theoretical calculations for the total age of the Earth, based on extrapolations from radioactive isotope data—see Unit 2, p. 43.)

chondrites, achondrites, stony irons, irons

There are four classes of meteorite: chondrites, achondrites, stony irons, and irons. The chondrites are in general more comparable in chemical composition to the Sun (determined from atomic spectra, Unit 6, p. 32) than rocks of the Earth's crust. On the other hand, the less abundant achondrites resemble some terrestrial igneous rocks. The great variety of types of meteorites suggest that they are derived from a number of parent bodies, ranging up to several hundred kilometres in diameter. They are unlikely to have been bigger than this because of the general absence of high-pressure minerals (e.g. garnet).

27.1.3 The Moon

The Moon is a much larger body than the inferred planetary parents of meteorites: 3 500 km in diameter compared with a possible 700 km or so for the largest meteoritic parents. The radio programme of Unit 26 describes the surface features of the Moon, so you probably already appreciate the vast differences between the surface features of our own planet and its companion.

Now read pp. 101–8 of Understanding the Earth, *starting at paragraph 2 on p. 101 and stopping at the end of the section entitled 'Lunar surface and its composition'.*

As you go through this material, try and answer the following questions (you might like to look up the notes for radio programme 26 as well). Note your answers down and afterwards compare them with our commentary.

1 What are the two main kinds of surface features of the Moon?

2 What processes have been suggested to account for the formation of the Moon's major surface features?

3 How does the rock recovered so far from the Moon differ from the Earth's crust and meteorites?

4 Can the formation of lunar rocks be compared with those from the Earth's crust?

When you have finished reading pp. 101–8, return to this text.

You should have noted down some of the following points whilst reading this extract.

maria
lunar highlands

1 The major surface features of the Moon are the comparatively flat, circular maria or 'seas', and the lunar highlands or 'continental' areas. (These features are in some ways comparable to those of the Earth's crust, as the maria are thought to be composed of a high density basaltic type material, not much different from the Earth's oceanic crust, while the highlands are thought to be formed of a lower density feldspar rich rock called anorthosite, possibly analogous to our own sialic continental crust).

2 Both these areas are pock-marked with myriads of craters. Professor Kopal suggests that volcanism might have played a minor role in sculpturing the lunar surface. However, as you will see later in this Unit, experimental evidence supports the possibility that a period of major outgassing† early in the Moon's history could have produced many of the craters. No features have been found on the Moon to indicate folding or major lateral crustal movement.

outgassing

3 The textures of the rocks recovered from the Moon are in many cases like those of some fairly coarse-grained igneous rocks of basaltic composition found on the Earth. However, the oxygen and silicon content of these rocks is rather lower than the average composition for the Earth's crust, whereas they are relatively enriched in titanium and magnesium. (This description refers to rocks collected from the maria. Data are not yet available on the possible anorthosites from the highlands.)

4 The surface of the Moon seems to be composed of loosely-packed material much of which has been derived from the break-up of pre-existing rocks by meteoritic erosion of the lunar highlands. The texture and composition of the lunar rocks suggests that they have cooled from temperatures of around 1 000 to 1 200° C, comparable with temperatures of terrestrial basaltic lavas. Unlike the materials now forming on the Earth's crust, the composition of the lunar rocks suggests that they formed in a reducing environment, similar to that which is postulated for the early history of the Earth (see p. 18 of this Unit).

27.1.4 Planetary atmospheres

Meteorites and the Moon are the only extraterrestrial objects so far available for direct sampling. Optical astronomy has, however, yielded a considerable amount of information concerning the planets; in addition, measurements of Mars and Venus made by radar, and from space probes, have supplemented this data. We should consider how this kind of evidence fits theories which try to account for the origin and evolution of the Solar System.

As you have seen in Unit 22, the planets forming the Solar System can be divided, on the basis of their physical properties, into an inner and outer group. This basic division is also reflected in their atmospheric compositions.

The gases present in planetary atmospheres are detected by analysing the spectra of light originating from them. As described in Unit 6, the spectrum of white light passing through a gas is modified by the introduction of absorption lines. Similarly, the emission of light produced by the excitation of molecules during absorption of the other wavelengths also characterizes the composition of the gas. The emission is also temperature controlled, and so it is possible to measure both atmospheric compositions *and* temperatures. Of course, we must subtract the absorption effects of the Earth's atmosphere when determining the gaseous composition of the atmospheres of other planets. Fortunately this is not too difficult, because of the motions of the planets relative to one another. They are in fact moving sources of reflected light. The wavelength of any radiation is modified according to the speed of the source relative to an observer. An every-day example is the change in pitch of the whistle of a passing train; as it comes towards you the whistle is high pitched, but as it passes and moves away the pitch is lowered. Of course, to the driver

Doppler effect

the note stays the same. This change in pitch of sound due to the relative speed of the source is one example of the *Doppler effect*. In the case of light, when the light source is moving towards an observer, the wavelength, like that of sound, is shortened; when the source is moving away it is lengthened.

If a source of white light was moving away from you at high speed (relative to that of the speed of light) in which direction would the overall colour of the light be shifted, to the blue end or the red end of the spectrum?

It would become redder because the source is receding so the wavelength is increased; hence the term red shift. In fact, red shift is particularly apparent in stars that are extremely distant from us and are moving away at a velocity of anything up to half the speed of light. In the case of the Earth and other planets the velocity differences are much smaller, but they are sufficient for the Doppler effect to be detected. This means that the absorption lines produced by gases on other planets do not exactly coincide with those produced by the same gases in the Earth's atmosphere. You can see this very well in Figure 1. In fact, spectral investigations of this sort form the basis of modern astronomy. For instance, the abundance of the elements in the Sun was obtained in this way, the Doppler shift being produced by the Sun's rotation.

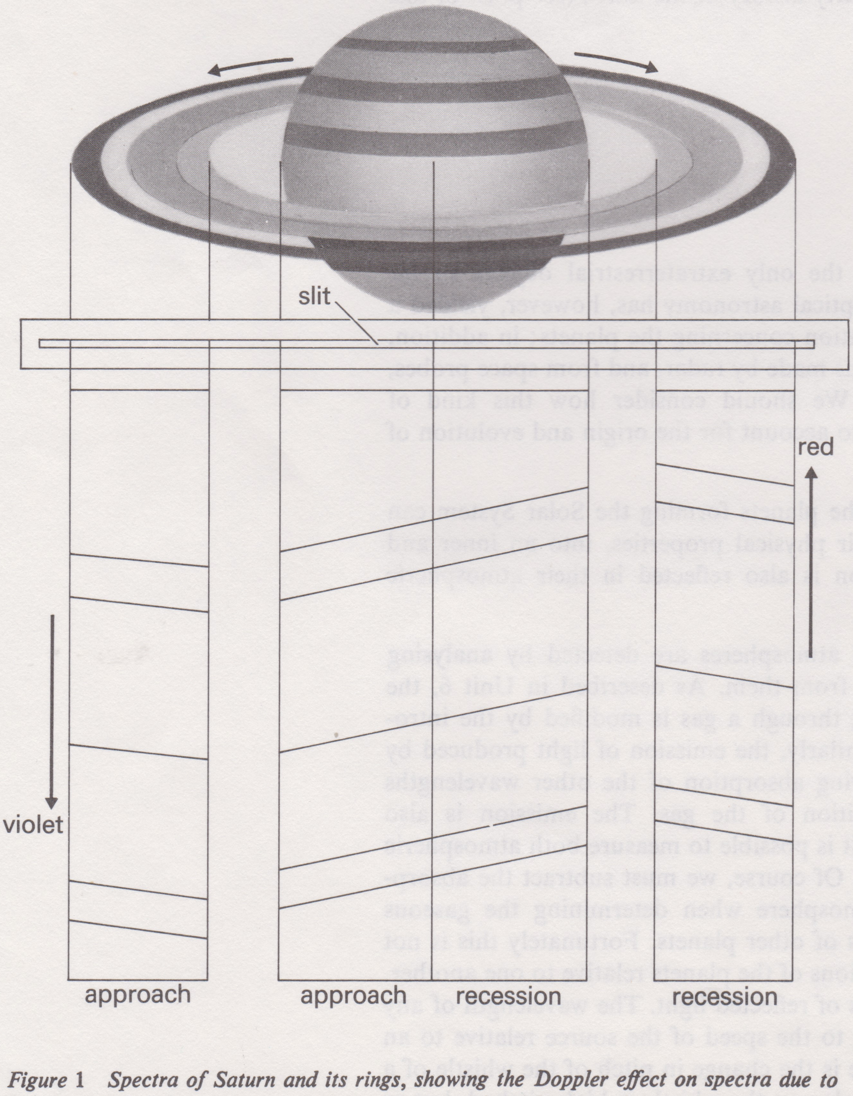


Figure 1 Spectra of Saturn and its rings, showing the Doppler effect on spectra due to rotation. Red shift occurs in the spectrum received from the part of the rings moving away from the Earth. The reverse occurs for that part of the rings moving towards the Earth.

Now to return to planetary atmospheres. When reading the summary given here, bear in mind the following.

1 Spectral measurements of the atmospheres of planets can only be made on the outer parts of these atmospheres.

2 Certain components of planetary atmospheres may not reach higher levels as they are frozen out. For example, water vapour condenses to ice in the Earth's atmosphere at a height of between 10 and 15 kilometres. On outer planets such as Neptune and Uranus, where temperatures are much lower than those on Earth, gases such as NH_3 would certainly freeze out and would not be detectable by spectral observations.

Table 1 summarizes our knowledge of the compositions of the atmospheres of the planets. Obviously the present composition of these atmospheres depends both on the evolutionary history and on the composition of the original material which accumulated to form the planets. Many astronomers believe that this original material must have had a composition very similar to that of the Sun.

Table 1 The composition of planetary atmospheres

	I *Observed* ( ) indicates trace only	II* *Predicted* (on ability to retain C, O, N, H compounds and He)
Mercury	—	
Venus	CO_2 (H_2O)	
Earth	N_2 O_2 (CO_2, H_2O, He, NH_3, CH_4)	
Mars	CO_2 (H_2O)	
Jupiter	H_2O, CH_4, NH_3	
Saturn	H_2O, CH_4, NH_3	
Uranus	H_2O, CH_4, NH_3	
Neptune	H_2O, CH_4, NH_3	
Pluto	—	

** Column II to be completed by student (see p. 12).*

observed and predicted compositions of planetary atmospheres

There is another important factor which will influence the final composition of a planet's atmosphere. This is the planet's *escape velocity*. A spacecraft must reach a velocity of 40 000 km per hour (or 25 000 miles per hour) in order to leave the Earth's gravitational influence. The same applies to gas molecules, which, as you will remember from Unit 5, are in a state of constant motion. Remember too that the Maxwellian distribution of molecular velocities in a gas is also temperature dependent (Unit 5, p. 21).

The escape velocity of a planet is defined as

$$\sqrt{\frac{2GM,}{R}}$$

where G is the universal gravitational constant, M is the planetary mass, and R is the planetary radius. As many molecules in a gas are moving much faster than the mean molecular speed, the latter must be less than one-sixth of the escape velocity of a planet if the gas is to be retained. One-sixth of the escape velocity of each planet is plotted against its inferred surface temperature on Figure 2, together with the mean variation with temperature of the molecular speed of gases that are considered to have been present in the primary atmospheres of the planets.

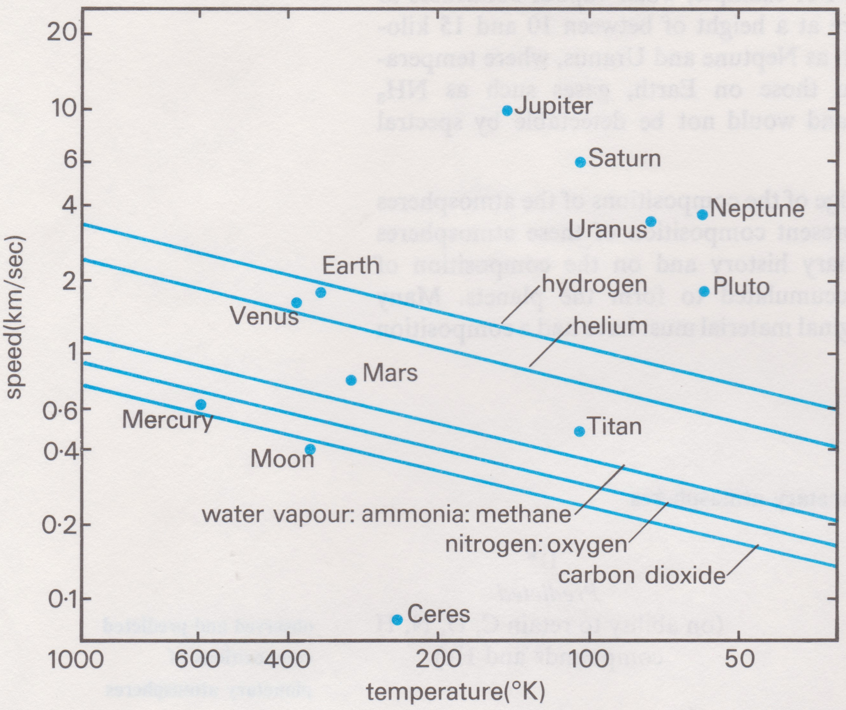


Figure 2 Inferred surface temperatures of the planets plotted against one-sixth their escape velocities (dots), and the mean molecular speeds of common gases plotted against temperature in degrees Kelvin (lines).

The elements or compounds included on Figure 2 are those which are considered to be the most common in the universe. Therefore, any primary atmosphere accumulating around the planet is likely to contain a high proportion of these. Assuming all the planets to have had an atmosphere composed of compounds or molecules of C, O, N, H, and He, determine the atmospheric composition that could be retained by each planet at its present-day temperature. Put your conclusions in column II of Table 1.*

The giant outer planets—Jupiter, Saturn, Uranus, and Neptune—have almost certainly retained all of their original atmospheres. Even hydrogen, the gas with the highest molecular velocity, was unable to escape, which accounts for the very high proportion of methane and ammonia in the atmospheres of these planets. The predicted atmospheric composition for the minor planets differ substantially from the observed ones (Table 1). For example, Mars and Venus have lost everything except CO_2, while Earth has lost almost all of its original methane and ammonia.

How have these gases been lost from original planetary atmospheres?

We have already stated that the molecular velocities of gases are temperature dependent. From Figure 2, you can see that an increase in planetary temperature would produce atmospheric compositions more closely corresponding to those we observe today, particularly for Mars, Venus

**The answers are given at the top of p. 14.*

and Earth. It seems feasible that the initial composition of planetary atmospheres was modified by a period of planetary heating and resultant outgassing.

As will become apparent in a later section, the idea that the original atmospheres of the planets, including the Earth, contained gases such as methane and ammonia is extremely important when considering the mechanism by which life may have originated on the Earth.

27.1.5 The solid planets

The density difference between the inner and outer planets has already been mentioned (Unit 22, Table 1). The average density of the inner planets is 5 200 kg m^{-3}, which suggests that the solid part of the inner planets is very similar in composition to that of the Earth. In contrast, the low density of the outer planets (690 to 2 270 kg m^{-3}) suggests that they are largely composed of hydrogen compounds. However, recent measurements of the thermal output of Jupiter and Saturn suggest that both bodies are emitting more heat than they receive from the Sun.

What does this suggest?

This raises the possibility that the solid parts of these planets, which are masked by a thick mantle of reducing gases such as CH_4 and NH_3, contain radioactive materials, which are decaying, and producing heat. By the end of the century, there may be seismometers on the other inner planets (as there are on the Moon), enabling their structure to be determined as has been done for the Earth. In the meantime we must make the most use of the meagre evidence available to us.

Can you remember why we suggested that the Earth has an iron core?

In Unit 22 it was suggested that the Earth has an iron core on the grounds of the density distribution as calculated from seismic evidence, computations based on the Earth's moment of inertia, and comparisons with meteorite compositions. There is confirmitory evidence for this in that the generation of the Earth's magnetic field can be accounted for by invoking motions in a liquid Fe-core. So the question arises: can we observe magnetic fields around the other planets? Recent space probes have shown that no significant magnetic fields surround either Venus or Mars. The results from Venus are perhaps surprising, because this planet has an almost identical density and size to that of the Earth. However, the most recent measurements suggest that Venus has a period of rotation (243 Earth days) which is longer than that of its orbital period (225 Earth days). The hypothetical model for the generation of the Earth's magnetic field not only invokes a liquid iron core, but also the Earth's relatively rapid rotation period. Thus the absence of a magnetic field around a planet is not conclusive proof for the absence of a liquid iron core.

There is only one planet, Jupiter, around which a magnetic field has been observed. The observations are indirect; radio emissions received from that planet are comparable to those detected from the Earth's magnetosphere. It is possible that the magnetic field around Jupiter is generated not by a liquid iron core, but by a liquid hydrogen core. Pressures within this vast planetary body are certainly sufficient to convert gaseous hydrogen into a liquid, and may well be sufficient to produce a 'crushed' state of matter in which the normal regular arrangement of electrons around

You should have predicted the following gases in column II of Table 1.

Mercury	CO_2
Venus Earth	CO_2, N_2, O_2, H_2O, NH_3, CH_4, possibly He
Mars	CO_2, N_2, O_2, H_2O, NH_3, CH_4
Jupiter Saturn Uranus Neptune Pluto	CO_2, N_2, O_2, H_2O, NH_3, CH_4, He, H_2

nuclei is broken down. The hydrogen within Jupiter's core may therefore consist of a super-conducting material which would generate the very strong magnetic field that is suggested by the radio emission of this planet.

It has been suggested that the inner planets are the products of the break-up of two earlier protoplanets. Mercury and Venus may have formed from an inner protoplanet, and that the Earth, Moon and Mars from an outer one. Perhaps a third protoplanet broke up to produce the present-day asteroid belt. You can see from Table 2 that the computed densities of the two inner protoplanets are almost identical. The break-up of these protoplanets may have resulted in the loss of their original atmospheres.

protoplanets

Table 2

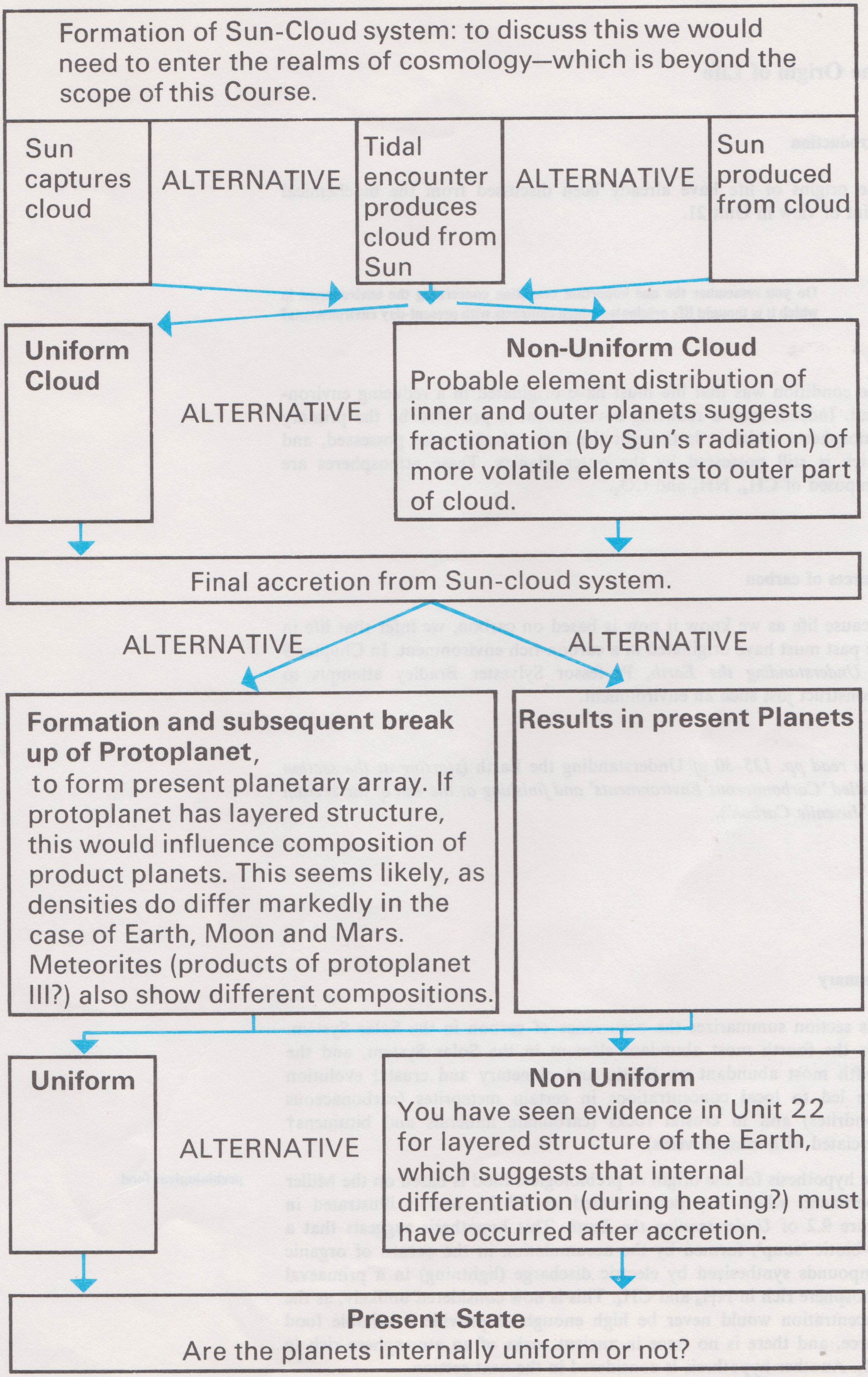
	Mass 10^{24} kg	Density kg m^{-3}
Mercury	0.330	5 470
Venus	4.872	5 240
PROTOPLANET I	5.202	5 250
Earth	5.974	5 510
Moon	0.0731	3 340
Mars	0.639	3 900
PROTOPLANET II	6.687	5 270

27.1.6 The origin of the Solar System

Now read pp. 62–8 of Chapter 3 of Understanding the Earth, *starting at the section entitled 'Origin of the Earth and Planets'.*

Summary

The events which may have occurred during the evolution of the Solar System are summarized in the 'flow chart' given on p. 15. At each stage of evolution there are alternative hypotheses; perhaps as we learn more about the Solar System some of these alternative hypotheses will be eliminated.



Formation of Sun-Cloud system: to discuss this we would need to enter the realms of cosmology—which is beyond the scope of this Course.

Non-Uniform Cloud

Probable element distribution of inner and outer planets suggests fractionation (by Sun's radiation) of more volatile elements to outer part of cloud.

Final accretion from Sun-cloud system.

Formation and subsequent break up of Protoplanet, to form present planetary array. If protoplanet has layered structure, this would influence composition of product planets. This seems likely, as densities do differ markedly in the case of Earth, Moon and Mars. Meteorites (products of protoplanet III?) also show different compositions.

Non Uniform

You have seen evidence in Unit 22 for layered structure of the Earth, which suggests that internal differentiation (during heating?) must have occurred after accretion.

Present State

Are the planets internally uniform or not?

27.2 The Origin of Life

27.2.1 Introduction

The origins of life have already been discussed from the biochemical point of view in Unit 21.

Do you remember the one important condition concerning the environment in which it is thought life originated which contrasts with present-day environments?

The condition was that life must have originated in a reducing environment. Indeed, such a reducing environment is provided by the primary atmospheres which it is thought the inner planets once possessed, and which is still possessed by the outer planets. These atmospheres are composed of CH_4, NH_3 and CO_2.

27.2.2 Sources of carbon

Because life as we know it now is based on carbon, we infer that life in the past must have originated in a carbon-rich environment. In Chapter 9 of *Understanding the Earth*, Professor Sylvester Bradley attempts to reconstruct just such an environment.

Now read pp. 125–30 of Understanding the Earth *(starting at the section entitled 'Carbonaceous Environments' and finishing at the end of the section on 'Juvenile Carbon').*

Summary

This section summarizes the occurrence of carbon in the Solar System. It is the fourth most abundant element in the Solar System, and the twelfth most abundant on Earth, and planetary and crustal evolution have led to local concentrations in certain meteorites (carbonaceous chondrites) and in crustal rocks (carbonate minerals and bitumens† associated with mineral veins).

prebiological food

One hypothesis for the origin of prebiological food is based on the Miller experiment, which was demonstrated in TV 21, and is illustrated in Figure 9.2 of *Understanding the Earth*. This hypothesis suggests that a pre-biotic 'soup', formed by the accumulation in the oceans of organic compounds synthesized by electric discharge (lightning) in a primaeval atmosphere rich in NH_3 and CH_4. This is now considered unlikely, as the concentration would never be high enough to provide a suitable food source, and there is no trace in ancient rocks of an atmosphere rich in CH_4. Another hypothesis is considered in the next section.

27.2.3 A theory for the origin of life

On pp. 130–2 of *Understanding the Earth*, Professor Bradley describes an isotopic method which attempts to label carbon as juvenile, or biogenic. If you wish, you may read this as black-page material.

The remainder of Chapter 9 discusses the evidence in the geological record concerning the origin of life, and relates experimental work to this, and to organic structures and compounds in meteorites.

Now read pp. 132–9, starting with the section on 'Carbon in early Precambrian rocks' and finishing with that on 'Environmental parameters for the Origin of Life'.

Summary

In South Africa, carbonaceous sedimentary rocks over 3 000 Ma old contain both microfossils and organic compounds, the former being comparable to the 'organized elements' of carbonaceous meteorites.

Experimental results have shown that carbonaceous organic compounds can be synthesized from a mixture of gases in a reducing atmosphere subjected to an energy source. It is believed that such conditions existed during periods of outgassing accompanied by electric discharges which provided the energy source. The carbonaceous products of meteorites are believed to have formed at such times under fluidizing conditions. Fluidization experiments have produced craters similar in form to those of the Moon and Mars, perhaps indicating that such phenomena were a common feature of early planetary evolution. It is possible that suitable conditions for the synthesis of organic compounds existed during the early hot outgassing phase of planetary development. Such compounds may have accumulated in sufficient quantities to form the prebiological food necessary for life to originate and reproduce. Sites of such accumulation might have been bituminous slicks along the beaches of the Earth's primaeval ocean, or along the abiogenic† oil/water interface in underground oil pools.

Once life was established, the chemical conditions of the outer parts of the Earth's crust and its hydrosphere and atmosphere were inevitably to change from a reducing to an oxidizing environment.

27.3 The Evolution of Life and the Atmosphere

27.3.1 The geological record

It has already been suggested that the Earth's present atmosphere is secondary, accumulating after a primary atmosphere has been driven off during a period of heating. Furthermore, it appears that this secondary atmosphere has changed from a reducing (or strictly non-oxidizing) one to an oxidizing one during the history of the Earth. How and when did the composition change? The geological record gives us some clues as to how the secondary atmosphere has changed through time. This atmosphere probably consisted of a mixture of gases given off during volcanic activity; these would include H_2O, CO_2, N_2, HCl, H_2 and S. Let us examine the possible fate of these volcanic products during the evolution of the atmosphere, consulting Figures 2 and 3.

1 Of the volcanic gases, only hydrogen (H_2) has a molecular speed sufficiently high to escape the Earth's gravity. This would leave H_2O, CO, CO_2, N_2, HCl, and S.

2 H_2O would condense to form the oceans, in which HCl would dissolve, and which in turn would dissolve crustal rocks to give soluble chlorides (NaCl forms just over 50 per cent of dissolved salts in sea water). CO_2 would also dissolve in water (see TV notes of Unit 24) and the resultant carbonic acid would attack crustal rocks. For example, a much simplified summary of the weathering of feldspar is given below:

$$CO_2 + 6H_2O + \underset{\substack{\textit{orthoclase}\\ \textit{feldspar}}}{2KAl\,Si_3O_8} \longrightarrow \underset{\textit{clay mineral}}{Al_2Si_2O_5(OH)_4} + \underset{\substack{\textit{silicic}\\ \textit{`acid'}}}{4\,SiO(OH)_2} + \underset{\textit{solution}}{K_2CO_3}$$

Sulphur would combine with other elements in the Earth's crust: much of it is now present in the mineral iron pyrites (FeS_2), which is present in small quantities in most sedimentary rocks.

3 In Figure 3, you will see that around 1 500 Ma ago, banded ironstone formations† gradually gave way to red beds.† The latter are sediments, such as sandstones and shales, stained red by haematite (Fe_2O_3). Banded ironstone formations (BIF for short) contain alternations of haematite and silica (in a mineral form termed chert), and siderite ($FeCO_3$) and silica. The mineral assemblage of the BIF is most likely to form in *reducing* or *non-oxidizing*, slightly acid conditions. But haematite *alone* is more likely to form in oxidizing conditions (see Fig. 13.12 in *Understanding the Earth*). In rocks older than about 1 500 Ma, the occurrence of pyrite sands† suggests an environment lacking in oxygen, as today pyrite grains would be oxidized during transportation and deposition. Sulphates, which are produced by atmospheric oxidation of sulphides, first appear in the geological record a little over 1 000 Ma ago (Fig. 3). So perhaps sometime around 1 500 Ma ago, the atmosphere contained appreciable quantities of oxygen liberated by photosynthesis. It is interesting to note that the first fossils resembling photosynthetic organisms (eucaryotes) appear just before this time (Fig. 3). The oxygen content of the atmosphere then probably increased (as recorded by the appearance of more complex life forms which presumably needed higher O_2-content ratios, and the increase in the ratio of Fe_2O_3 to FeO in fine grained sediments, which are also often stained red by haematite, and so termed red beds).

4 The carbon present in the original secondary atmosphere was first 'fixed' into carbonates such as limestones about 2 500 Ma ago (Fig. 3) and later into fossil fuels, such as coal, which first appears in the record about 400 Ma ago.

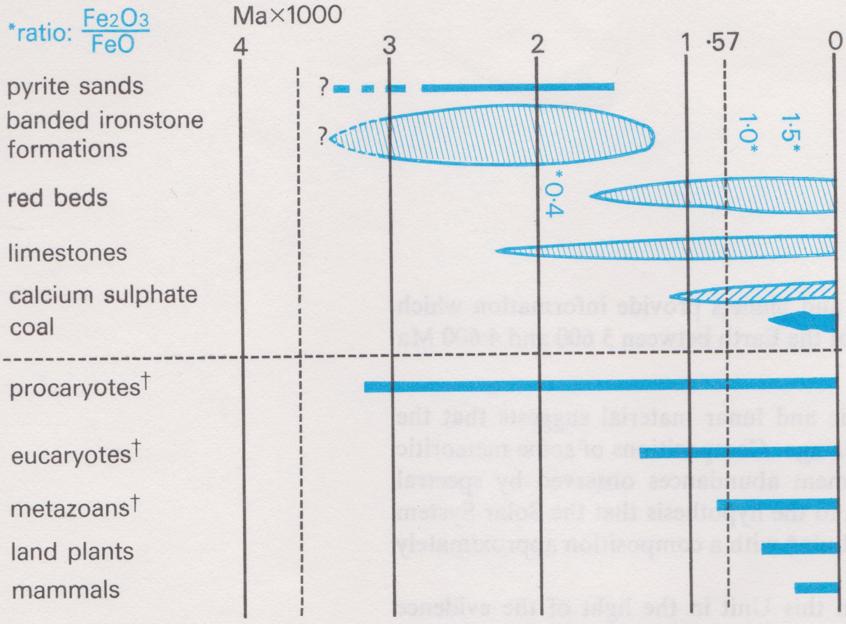


Figure 3 Key items in the geological record. The top half shows the distribution in the record of some key rock types, while the bottom half shows the evolution from lower to higher forms of life.

It thus seems likely, from studies of the geological record, that the secondary atmosphere changed from a non-oxidizing to an oxidizing one about 1 500 Ma ago. It is probable that the present-day atmosphere of Venus, consisting largely of CO_2 at a temperature of several hundred degrees centigrade, is much like that of our own planet some 3 600 to 4 000 Ma ago. On Venus, the high temperatures and an anhydrous environment ensure that the reaction of CO_2 with crustal rocks is not possible, and so CO_2 remains in the atmosphere.

27.3.2 Oxygen and evolution

When considering the evolution of life and atmosphere we should also take into account the effects of ultra-violet radiation on atmospheric gases and life itself.

Now read Chapter 10 (pp. 142 to 149) in Understanding the Earth.

When you have finished this Chapter, attempt Self-Assessment Questions 14–16.

The theory of Berkner and Marshall explains the relatively sudden appearance of abundant metazoan† life only about 600 Ma ago, and may also account for other significant changes in evolutionary rates since that time. The major modification that has been made to the theory since its publication is that free oxygen in quantities sufficient for oxidative respiration was present in the atmosphere perhaps 1 300 Ma ago, since eucaryotic† cells have been found in rocks of this age. As most living eucaryotes need oxygen to respire, it is reasonable to assume, applying the principle of Uniformitarianism, that their ancestors did also. If the subject of the evolution of life and its possible causes interests you, you may like to read (as black-page material) Chapters 11, 12, 14 and 18 in *Understanding the Earth*.

Summary of Unit 27

Present-day studies of meteorites and planets provide information which can be used to infer the evolution of the Earth between 3 600 and 4 600 Ma ago.

Radiometric dates from meteoritic and lunar material suggests that the Solar System was formed 4 600 Ma ago. Compositions of some meteoritic materials are very similar to element abundances observed by spectral methods for the Sun. This has led to the hypothesis that the Solar System has developed from an original nebula† with a composition approximately like that of the Sun.

The origin of life is considered in this Unit in the light of the evidence afforded from the geological record, and from extra-terrestrial materials. Carbon, nitrogen and hydrogen were abundant in the early phases of planetary formation, and probably combined and reacted to form organic compounds. At a later stage, these compounds may have been concentrated in quantities sufficient for life to develop. This theory has arisen out of the study of carbonaceous chondrites—a class of meteorites containing organic compounds. In fact, such processes of abiogenic synthesis of organic compounds probably occur on Earth at the present time in association with igneous activity. The occurrence of 'organized elements' in meteorites similar to structures formed in experiments attempting to simulate conditions necessary for the origin of life supports the theory that life originated very early in the Earth's history. The geological record confirms this view, as the oldest rocks remaining relatively unaffected by metamorphism contain similar 'organized elements'.

The origin and evolution of life and the development of the Earth's atmosphere appear to be intimately linked. There is little doubt that the Earth's present atmosphere is secondary in origin; the initial, or primary atmosphere (similar to atmospheres of the outer planets) having been driven off by a period of heating. This primary atmosphere was rich in compounds of C, N and H, and probably played a major role in events leading to the origin of life. The secondary atmosphere probably accumulated from volatiles given off during volcanic activity, and so at first would have contained CO_2, H_2O and N_2. CO_2 has been fixed by weathering, and later by life itself, and oxygen has been released by the photo-dissociation of water, followed by its release from CO_2 during photosynthesis.

Further Reading

If any of the topics discussed in this Unit particularly interested you, we suggest you read a selection of the following (as black-page material).

1 *Understanding the Earth.*
Chapter 1, 'The Composition of the Earth'.
Chapter 11, 'The Primitive Earth'.
Chapter 12, 'Evolution in Environments'.
Chapter 14, 'Evolution and the Fossil Record'.

2 George Abell, *Exploration of the Universe.* Holt, Rinehart and Winston (2nd edition, 1969).
Chapter 12, 'The Solar System in General'.
Chapter 13, 'The Earth Moon System'.
Chapter 14, 'The Other Planets'.
Chapter 15, 'The Minor Planets'.
Chapter 17, 'Meteoroids, Meteorites and Meteors'.

3 *Scientific American*, September 1970.
Special issue on the Biosphere, especially the following articles.
G. Evelyn Hutchinson, 'The Biosphere'.
Preston Cloud and Aharon Gibor, 'The Oxygen Cycle'.

Acknowledgements

Grateful acknowledgement is made to the following source for illustrations used in this unit:

HOLT, RINEHART AND WINSTON for Figs. 1 and 2 in, George Abell, *Exploration of the Universe.*

Grateful acknowledgement is also made to Patricia McCurry, Research Assistant in Earth Sciences, for her help during the final stages of preparation of Units 24–27.

Appendix 1

Appendix 1 (White)

Glossary

ABIOGENIC Term usually applied to organic compounds formed by non-living processes.

BANDED IRON ORES Alternating layers of sedimentary rock consisting of Fe_2O_3 (haematite) and SiO_2 (silica) which laboratory investigations suggest formed in a slightly reduced environment.

BITUMEN Natural tar.

EUCARYOTIC CELL Cells in which nucleus and mitochondria are discrete bodies, enclosed within membranes (as distinct from procaryotic cells, which lack intracellular membranes and so do not have discrete cells).

METAZOAN Animal which is built up of many cells, individuals or aggregates of which may have specialized functions.

NEBULA Cloud of inter stellar gas or dust.

OUTGASSING Large-scale escape of gases during particularly intense volcanic activity.

PYRITE SANDS Detrital sandstones containing abundant grains of pyrite (FeS_2).

RED BEDS Sedimentary rocks (sandstones, siltstones and shales) stained red by Fe_2O_3, which formed in an oxidizing environment.

Self-Assessment Questions

Self-Assessment Questions

Question 1 (*Objective 1*)

Below are lists of statements relevant to the nature and location of the parent bodies of meteorites. Match the items in List A with those in List B.

List A	**List B**
Observation, terms	Explanations, hypotheses
1 Chemical analysis of observed falls.	A Fragments formed from the break-up of a planet once orbiting between Mars and Jupiter.
2 Wide variety of mineral compositions.	B Best approach to real extra-terrestrial elemental abundances.
3 Simultaneous photography from several points on the Earth's surface has enabled the trajectory of two recent meteorite falls to be calculated.	C Different sizes of parent bodies.
4 Numerous small planetary bodies situated between the orbits of Mars and Jupiter.	D Meteorites probably originate from the Asteroid belt.

Question 2 (*Objective 1*)

The two lists below contain statements relevant to the classification and composition of meteorites. Match the items from list A with those in list B.

List A	**List B**
1 Achondrites.	A Nickel-iron minerals and silicates in approximately equal amounts.
2 Stony irons.	B Class of meteorites which differs fundamentally from the rest, because they contain a hydrous mineral, and organic compounds.
3 Chondrites.	C Fe-Mg Silicates, usually anhydrous.
4 Irons.	D Chondrules.
5 Spheroidal aggregates approximately 1 mm in diameter.	E Elemental abundance ratios in general resemble those measured by spectral methods for the Sun.
6 Commonest silicate minerals in meteorites.	F Resemble terrestrial igneous rocks.
7 Carbonaceous chondrites.	G Nickel-iron alloy.

Question 3 (*Objective 1*)

The two lists below contain statements concerning the history and nature of the parent bodies of meteorites.

Match the items in List 1 with those in List 2.

List 1

1 Early heating sometimes caused fusion of material.

2 Average composition of iron meteorites closely corresponds to the average composition of metal components of chondrites.

3 Most meteorite minerals.

4 Meteoritic material is 4 600 Ma old.

5 General absence of 'high pressure' minerals in meteorite.

6 Most terrestrial crustal minerals.

List 2

A Radiometric dating.

B Formed in reducing anhydrous environment.

C Formed in hydrous oxidizing environment.

D Achondrites resemble igneous rocks found on Earth.

E Iron meteorites probably represent metal segregated by partial or complete melting of material of chondritic composition.

F Parent bodies must have been quite small.

Question 4 (*Objective 1*)

Summarize the major features of the principal types of meteorite by placing the appropriate letter or letters alongside each type.

Chondrites

Achondrites

Stony irons

Irons

A Contain Fe-Mg silicate minerals

B Contain Ni-Fe minerals

C Contain Chondrules

D Resemble terrestrial igneous rocks

E Contain hydrous minerals

F Contain organic compounds

Self-Assessment Questions

Question 5 (*Objective 1*)

Tick opposite the correct statements relating to the lunar maria and the lunar highlands.

	maria	*highlands*
1 Possibly formed by huge basalt type lava flows.		
2 Can be compared to Earth's ocean basins.		
3 Can be compared to Earth's continents.		
4 Extensively pock-marked by craters.		

Question 6 (*Objective 1*)

How is it possible to separate spectral measurements of planetary atmospheres from those of the Earth's atmosphere? Answer in less than 50 words.

Question 7 (*Objective 1*)

A planet's ability to retain an atmosphere of a given composition depends on:

	True	*False*
1 its temperature		
2 its escape velocity		
3 the thickness of its atmosphere		
4 its mass		
5 the strength of its magnetic field		

Question 8 (*Objective 2*)

Show the differences between the inner and outer planets by ticking in the appropriate columns against the list of statements given below.

	Inner	*Outer*
1 Densities about 5 000 kg m^{-3}.		
2 Atmospheres probably primary.		
3 Densities about 2 000 kg m^3.		
4 Possess several satellites.		
5 Atmospheres probably secondary in origin.		
6 Radii 8 000 km or less.		

Question 9 (*Objectives 3 and 9*)

Select items from the list below which are observations which provide evidence for antiquity of the Moon's surface features in contrast to those of the Earth.

	Antiquity of lunar surface features	*Relative youth of Earth's surface features*
1 About 60 per cent of the Earth's surface has formed during the last 200 Ma by sea floor spreading.		
2 The Moon has no atmosphere.		
3 Radiometric ages of lunar rocks are mostly older than 3 000 Ma.		
4 No features suggesting significant crustal movement have been observed on the Moon.		
5 Clear, sharp outlines of nearly all the Moon's surface features.		
6 Continental rocks (on Earth) that are over 3 000 Ma old only form a few per cent of the Earth's surface area.		

Question 10 (*Objective 1*)

Why is it suggested that the Moon, Earth and Mars were formed from one protoplanet, and Venus and Mercury from another?

Give your answer in one short sentence.

Question 11 (*Objective 1*)

Which of the following gases are used in the Miller experiment?

Tick appropriate item.

CO_2

CH_4

H_2O

O_2

N_2

NH_3

Question 12 (*Objective 1*)

Which of the following energy sources is used in the Miller experiment.

Tick appropriate item.

1 Combustion   2 Electric discharges   3 Ultra-violet radiation

Question 13 (*Objective 4*)

Calculate the escape velocity of Jupiter; its mass is approximately 19×10^{26} kg, and its radius is approximately 7.15×10^7m. ($G = 6.67 \times 10^{-11}$).

Select from the following.

1 $4.6–5.0 \times 10^4$ m/sec

2 $5.1–5.5 \times 10^4$ m/sec

3 $5.6–6.0 \times 10^4$ m/sec

4 $6.1–6.5 \times 10^4$ m/sec

5 $6.6–7.0 \times 10^4$ m/sec

6 $7.1–7.5 \times 10^4$ m/sec

Question 14 (*Objective 7*)

Oxygen was released into the Earth's early atmosphere by:

	True	*False*
1 photodissociation of CO_2		
2 photosynthetic organisms		
3 weathering of iron minerals		
4 photodissociation of H_2O		

Question 15 (*Objective 7*)

Match the events (given in list 1) which occurred (according to the Berkner and Marshall theory) during the build up of oxygen in the Earth's atmosphere with the statements in list 2.

List 1

1 First critical level.

2 Second critical level.

3 Urey effect.

List 2

A The O_2 level beyond which metazoan organisms would evolve.

B 10 per cent of the present oxygen content of the atmosphere.

C 0.1 per cent of the present oxygen level of the atmosphere.

D The O_2 level at which the amount of ozone in the upper atmosphere masks ultra-violet radiation and so stops the photodissociation of H_2O, preventing a further increase in O_2 levels.

E The O_2 level beyond which life can evolve on land.

F 1.0 per cent of the present oxygen level of the atmosphere.

Question 16 (*Objective 1*)

It is probable that the atmospheres of Venus, Earth and Mars are secondary in origin. Which statements below concerning this hypotheses are true?

	True	*False*
1 Because their present escape velocity is too low to retain gases.		
2 Because their atmospheric composition (in contrast to the outer planets) is not that which would be expected from the solar abundance of elements.		
3 Photosynthesis has modified their original atmospheres.		
4 Evidence from meteorites and the Moon suggests a period of heating early in planetary histories.		

Self-Assessment Answers and Comments

Question 1

1 B
2 C
3 D
4 A

Question 2

1 F
2 A
3 E
4 G
5 D
6 C
7 B

Question 3

1 D
2 E
3 B
4 A
5 F
6 C

Question 4

Chondrites: A, B, C, E, F.
Achondrites: A, D.
Stony Irons: A, B.
Irons: B.

Question 5

Maria: 1, 2 and 4.
Highlands: 3 and 4.

Question 6

Motion of the planets, either their rotation or their movement towards or away from the Earth as they orbit the Sun, causes a shift in their spectra (the Doppler effect). This permits absorption and emission lines to be distinguished from those produced in the Earth's atmosphere.

Question 7

1, 2 and 4 are correct (2 is proportional to 4).
3 and 5 are incorrect.

Question 8

Inner planets: 1, 5 and 6.
Outer planets: 2, 3 and 4.

Question 9

Antiquity of lunar surface features: 3.

Youth of Earth's surface features: 1 and 6.

Items 2, 4, 5; the fact that the Moon has no atmosphere, clear sharp topographic features and that no significant lateral crustal movement has occurred explain why the Moon's ancient surface has been preserved —but they do not in themselves provide *direct* evidence for the antiquity of lunar features.

Question 10

The densities of each protoplanet (calculated from those of the daughter planets) are almost identical (see Table 2).

Question 11

CH_4, H_2O, NH_3.

Question 12

2 is correct.
3 is also likely in the 'real' situation.

Self-Assessment Answers and Comments

Question 13

3 is correct. Remember, the escape velocity of a planet is defined as:

$$\sqrt{\frac{2GM}{R}} \quad \text{so} \quad \sqrt{\frac{2(6.67\times10^{-11})\times(19\times10^{26})}{7.15\times10^{7}}}$$

which gives, by cancelling the tens:

$$\sqrt{\frac{2(6.67)\times(19\times10^{8})}{7.15}}$$

$$= \sqrt{\frac{253.5\times10^{8}}{7.15}}$$

$$= \sqrt{35.45\times10^{8}}$$

$$= 5.95\times10^{4}\ \text{m s}^{-1}$$

As we 'rounded off' the mass and radius of Jupiter this value is not exact. The precise escape velocity of Jupiter is 5.75×10^{4} m s^{-2}.

Question 14

2 and 4 are true.

Question 15

1 A and F.
2 B and E.
3 C and D.

Question 16

1 False: these planets could retain CH_4 and NH_3 at their present temperatures.
2 True.
3 False: probably only true for the Earth.
4 True.

S.100—SCIENCE FOUNDATION COURSE UNITS

1 Science: Its Origins, Scales and Limitations
2 Observation and Measurement

3 Mass, Length and Time
4 Forces, Fields and Energy

5 The States of Matter

6 Atoms, Elements and Isotopes: Atomic Structure
7 The Electronic Structure of Atoms

8 The Periodic Table and Chemical Bonding
9 Ions in Solution

10 Covalent Compounds

11 } Chemical Reactions
12 }

13 Giant Molecules

14 The Chemistry and Structure of the Cell

15 } Cell Dynamics and the Control of Cellular Activity
16 }

17 The Genetic Code: Growth and Replication
18 Cells and Organisms

19 Evolution by Natural Selection
20 Species and Populations

21 Unity and Diversity

22 The Earth: Its Shape, Internal Structure and Composition

23 The Earth's Magnetic Field

24 Major Features of the Earth's Surface
25 Continental Movement, Sea-floor Spreading and Plate Tectonics

26 } Earth History
27 }

28 The Wave Nature of Light

29 Quantum Theory
30 Quantum Physics and the Atom

31 The Nucleus of the Atom
32 Elementary Particles

33 } Science and Society
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S 100 26 and 27

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